Final Report

Task Research Title: Physics of Regolith Impacts in Microgravity Experiment (PRIME)
NAG3-2400

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1. Introduction

Collisions between planetary ring particles and in some protoplanetary disk environments occur at low impact velocities ($v < 1$ m/s). In some regions of Saturn's rings, for example, the typical collision velocity inferred from observations by the Voyager spacecraft and dynamical modeling is a fraction of a centimeter per second. Although no direct observations of an individual ring particle exist, the abundance of dust in planetary rings and protoplanetary disks suggests that larger ring and disk particles are coated with a layer of smaller particles and dust – the "regolith." Because the ring particles and proto-planetesimals are small (cm to m-sized), the regolith is only weakly bound to the surface by gravity. Similarly, secondary impacts on asteroids by large blocks of ejecta from high velocity cratering events result in low velocity impacts into the asteroid regolith, which is also weakly bound by the asteroid's gravity.

At the current epoch and throughout their history, low velocity collisions have played an important role in sculpting planetary systems. In a one-Earth-gravity environment, it is not possible to experimentally determine the behavior of impact eject from such low velocity collisions. Impacts typically occur at speeds exceeding the mutual escape velocity of the two bodies. Thus, impacts at speeds on the order of 10 m/sec or less involve objects that are tens of meters across, or smaller.

This research program is an experimental study of such low velocity collisions in a microgravity environment. The experimental work builds on the Collisions Into Dust Experiment (COLLIDE), which has flown twice on the space shuttle. The PRIME experimental apparatus is a new apparatus designed specifically for the environment provided on the NASA KC-135 reduced gravity aircraft.

2. Description of Research

We designed, developed, tested, and successfully operated a new low velocity impact apparatus on the NASA KC-135. We performed ground-based impact experiments in a new apparatus for low velocity impacts in the laboratory to complement the reduced gravity experiments performed with the PRIME appartus (Figure 1). PRIME consists of eight identical PRIME Impact Chambers (PICs), an experiment mounting rack, and a PIC storage rack. Each PIC consists of an Aluminum baseplate and acrylic tops and sides, forming an airtight seal with an o-ring between the acrylic cover and the baseplate. The baseplate has bolt hole patterns allowing for a projectile launcher to be attached in one of four positions. This allows for impacts onto the target surface at angles of 30, 45, 60, and 90 degrees, and is an improvement over the proposal design for the experiment which only allowed for normal (90 degrees) impacts. The launchers use interchangeable back plates. Each back plate has a spring corresponding to a particular projectile velocity. This design allows for multiple parameters over the course of a four-day flight program on the KC-135. Targets consist of a variety of granular materials, including quartz sand, JSC-1, and JSC-Mars-1, each of which can be sieved to a variety of size distributions.

PRIME was flown on the KC-135 in five flight weeks: July 2002, August 2002, January 2003, April 2003, and May 2003. The quality of data varies widely from flight to flight. This is due to variations in the quality of the parabolas as well as an improvement in the configuration of the high speed camera from the first flights to the last flight week.

Unfortunately, a camera malfunction resulted in virtually no usable data from the April 2003 flight week. Negative-g spikes also ruined several impact opportunities due to turbulent weather conditions. The maximum possible number of impact experiments is 8/day, or 32 per flight week. The actual number of usable impact experiments obtained with PRIME in the five flight weeks is 85.

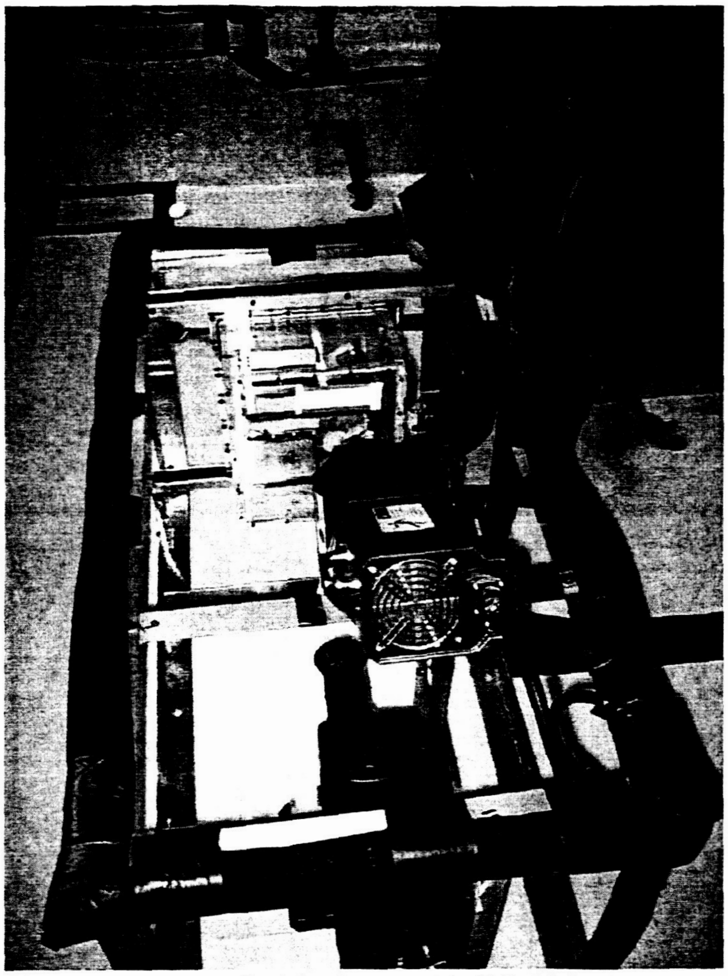

Figure 1: PRIME apparatus installed in the NASA KC-135, showing one PIC, a high speed camera head (bottom), and two strobe lights. The remaining PICs are swapped into this frame during the flight.

The PRIME target consists of unconsolidated granular material so that prior to the impact it is vulnerable to acceleration variations in the aircraft. Tests performed in the airplane in 2001 indicated that running the experiment on parabolas biased to 0.01g with the target surface parallel to the airplane floor would maintain a stable target layer while still allowing for measurements of slow ejecta velocities. This results in some positive residual acceleration during the impact of a few hundredths of a g, and even with biased parabolas some experiments were lost due to negative g spikes that lead to the target material dispersing prior to impact. Two example frames from PRIME impacts are shown in Figures 2 and 3.

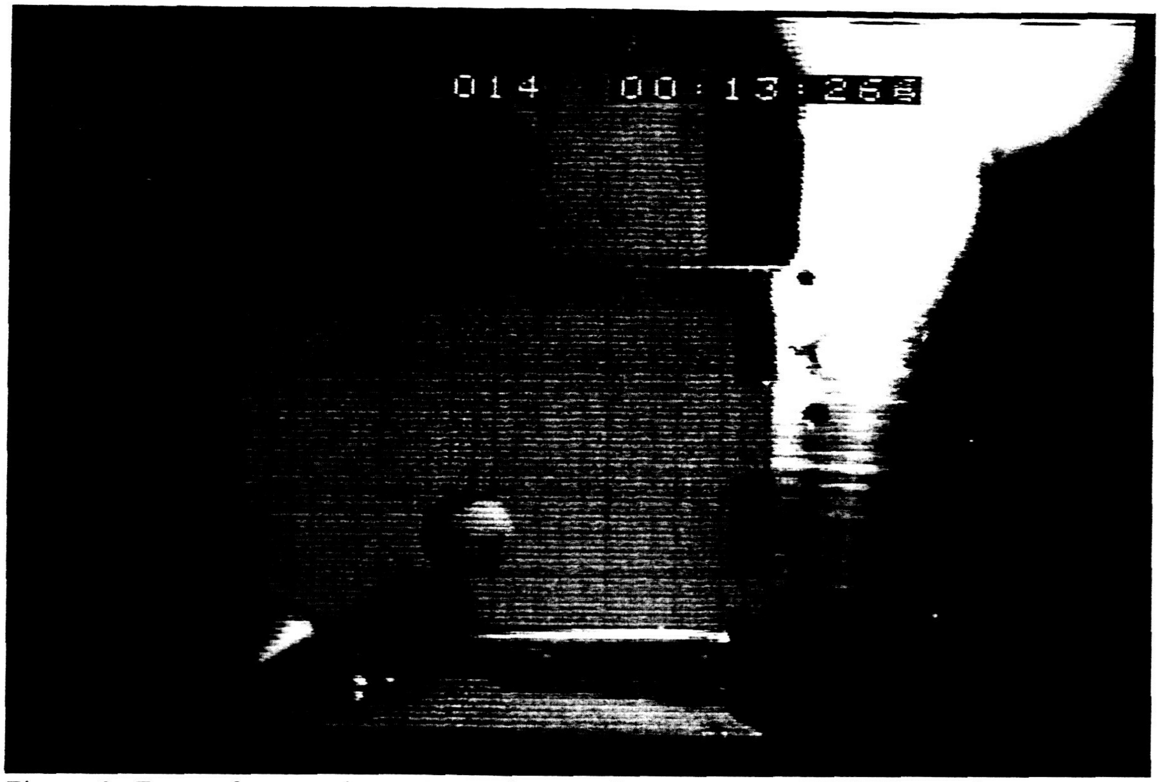

Figure 2: Frame from an impact experiment of a ¾-inch Delrin impactor into quartz sand just prior to the impact. The reflected image of the target and impactor is visible in the mirror at the top of the frame.

We are using the same analysis technique that has been successfully applied to the COLLIDE-2 data, using the Spotlight software provided by NASA Glenn Research Center to measure pre-impact and post-impact impactor velocities for coefficients of restitution and to measure ejecta velocities. An example of a tracked trajectory is shown in Figure 4.

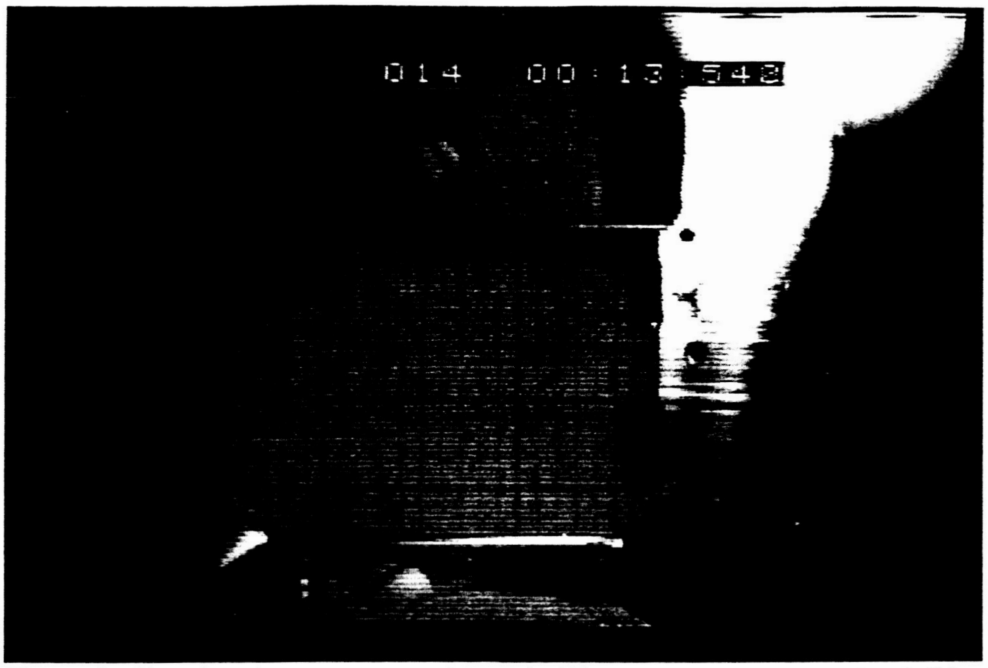

Figure 3: Shortly after the frame shown in Figure 1, the impactor is visible embedded in the target surface in both the direct (bottom) and reflected (top) views. The view in the mirror shows the crater produced by the impact, and the direct view shows sand ejecta produced in the impact.

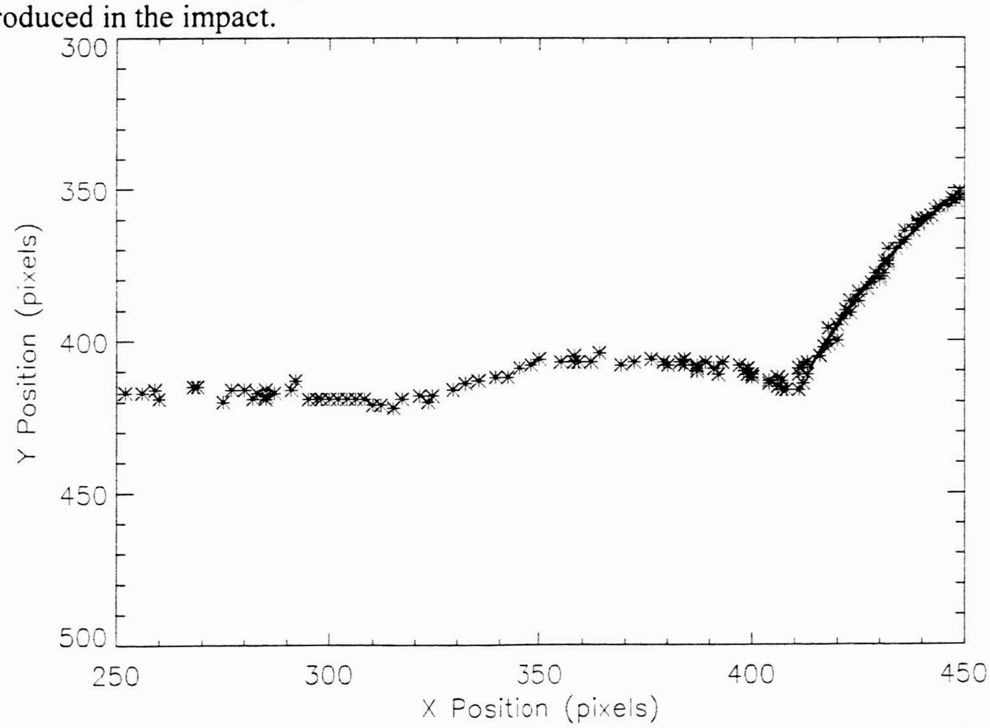

Figure 4: Tracked positions of the projectile from an oblique impact. The projectile begins at right and moves to the left. A parabola is fit to the segment at X>410 to provide the initial velocity and the residual acceleration from the airplane in the Y direction. In this case the acceleration was enough to cause the projectile to fall too quickly and it bounced off the right edge of the target tray at X=410, then follows another parabolic trajectory between X=320 and X=410 prior to impacting the target surface.

In general the target grains are not individually resolved, and the cloud of ejecta is frequently optically thick, preventing identification of individual ejecta grains. Instead we used the same technique applied to the COLLIDE-2 data which is qualitatively similar to PRIME data, though at lower temporal ar E atial resolution (Figure 5).

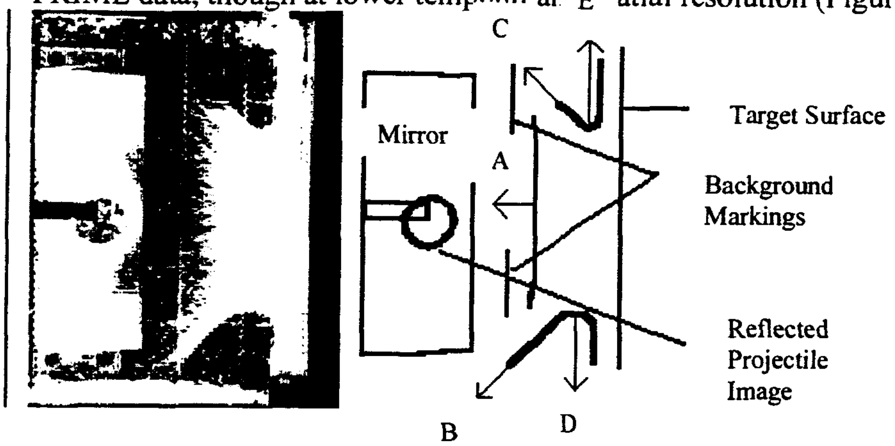

Figure 5: Still frame from one of the COLLIDE-2 impact experiments 0.3 seconds after impact, and schematic of the image frame. The target surface is vertical at right, and the projectile motion was horizontally from the left. An image of the projectile on the target surface is visible in the mirror at left. Lettered arrows indicate the points on the ejecta curtain that were tracked for this IBS, and blue lines identify some of the elements in the image. The lettered arrows indicated components of the ejecta curtain that are tracked to give characteristic ejecta velocities. This technique is used to determine ejecta velocities in the PRIME data.

Complementary ground-based data were also obtained at impact speeds between 100 and 240 cm/s, at normal incidence, into 2-mm diameter glass and acrylic beads, JSC-1, and quartz sand. The synthesis of this data, which has been presented at a number of conferences, will provide the first scaling relations for ejecta velocities and masses at low impact velocities (Figure 6). These experiments at 1 g provide more detailed information on the ejecta velocities, but are limited to higher impact velocities and only relatively high ejecta velocities can be observed in a 1 g environment (Figure 7). We have found that:

- Ejecta mass is not a simple function of kinetic energy;
- Fej(v) is power-law (like high-v impacts); maybe 2-component;
- Erosion/accretion boundary occurs at impact speeds of about 10-30 cm/s;
- Typical ejecta velocities are on the order of 10% of the impact velocity for normal impacts, and much higher for oblique impacts;
- Microgravity results indicate a far lower velocity threshhold for accretion than indicated by ground-based experiments by previous researchers;
- Spacecraft and astronaut activity on the surface of dusty objects, such as the Moon, will launch significant amounts of dust at speeds ranging from ~10 cm/s to a few m/s, depending on the nature of the surface disturbance (e.g. oblique or normal incidence).

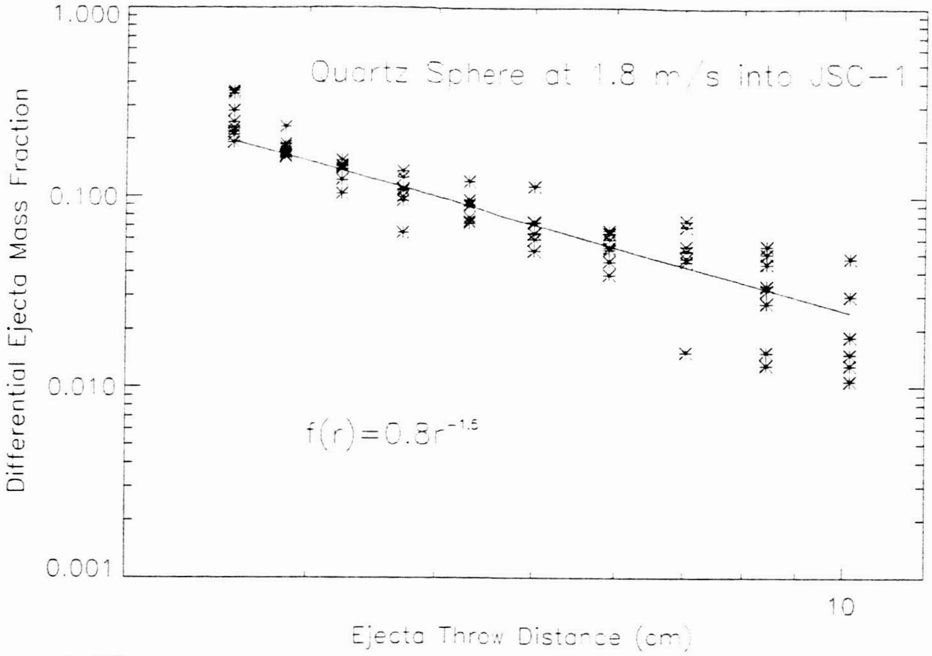

Figure 6: Ejecta velocity distribution (shown here as throw distance, related to velocity by impact angle) for impacts in the laboratory experiments.

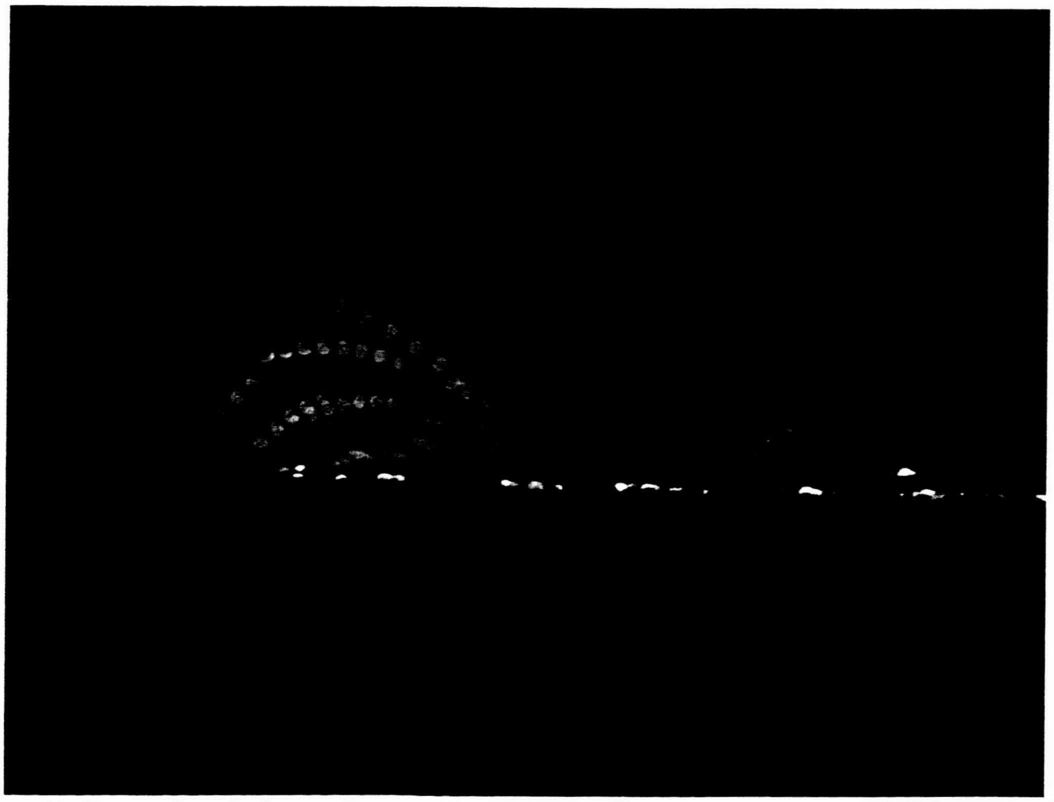

Figure 7: Example of ejecta (2 mm diameter acrylic spheres) illuminated by a strobed vertical laser sheet in a ground-based impact experiment, permitting direct measurement of the ejecta velocities of individual particles.

3. Publications and Reports.

Our results have been presented at the following meetings and in the following publications.

1. Colwell, J. E., and S. Sture 2000. Low Velocity Impact Experiments in Microgravity. Fifth Microgravity Fluid Physics and Transport Phenomena Conference, Aug. 9-11 2000, Cleveland OH, pp. 185-186.

2. Colwell, J. E., and M. Mellon 2002. Experimental Studies of Collisions in Planetary Rings and Protoplanetary Disks, 33rd Lunar and Planetary Science Conference, Mar. 11-15, Houston TX (Abs. #1757).

3. Colwell, J. E., S. Sture, A. Lemos 2002. Microgravity Impact Experiments: The PRIME Campaign on the NASA KC-135. 6th Microgravity Fluid Physics and Transport Phenomena Conference, Aug. 14-16, Cleveland OH.

4. Colwell, J. E., and S. Sture 2003. Experimental Studies of Low-Velocity Microgravity Impacts into Regolith. 34th Lunary and Planetary Science Conference, Mar. 17-21, Houston TX (Abs. 1904).

5. L. E. Crawford, C. M. Hrenya, and J. E. Colwell 2003. Low Velocity Collisions into Regolith: Simulation vs. Experiment. Annual Meeting of the American Institute of Chemical Engineers, San Francisco, CA.

6. Colwell, J. E., and S. Sture 2003. Experimental Studies of Low-Velocity Impacts into Regolith. *Bull. Amer. Astron. Soc.*, Vol. 35, 940.

7. Colwell, J. E. 2003. Low Velocity Impacts into Dust: Results from the COLLIDE-2 Microgravity Experiment. *Icarus*, **164**, doi: 10.1016/S0019-1035(03)00083-6.

8. Colwell, J. E., and M. Mellon 2004. Low-Velocity Impacts into Regolith. In preparation.

9. Colwell, J. E. 2004. Ejecta Velocities in Low-Velocity Impacts in Microgravity. In preparation.